~25 Years of "Beauty"ful Physics: Some Flavor of Heavy Flavor

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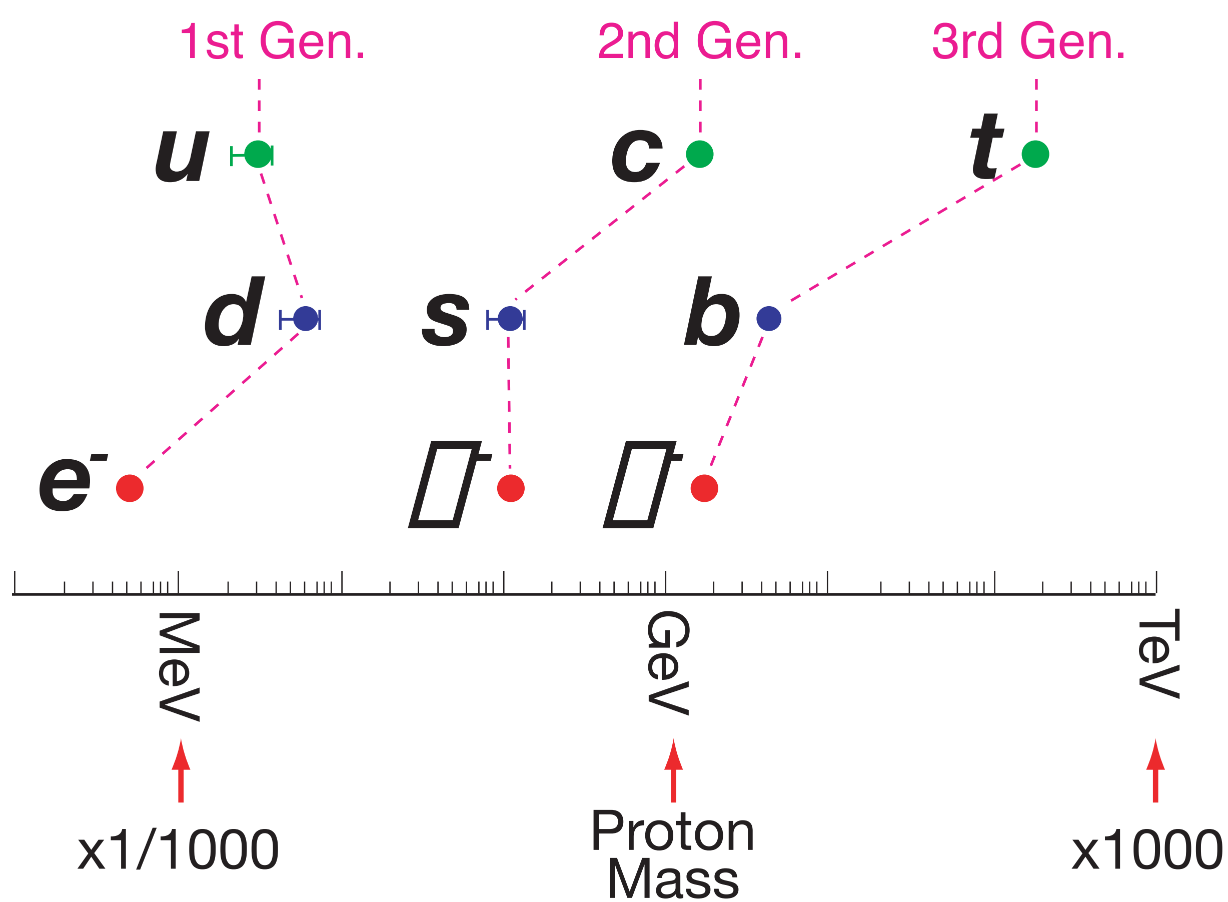
Indiana University

25th Anniversary of First $p\bar{p}$ Collisions at Fermilab – Symposium

Friday, 17 Dec. 2010

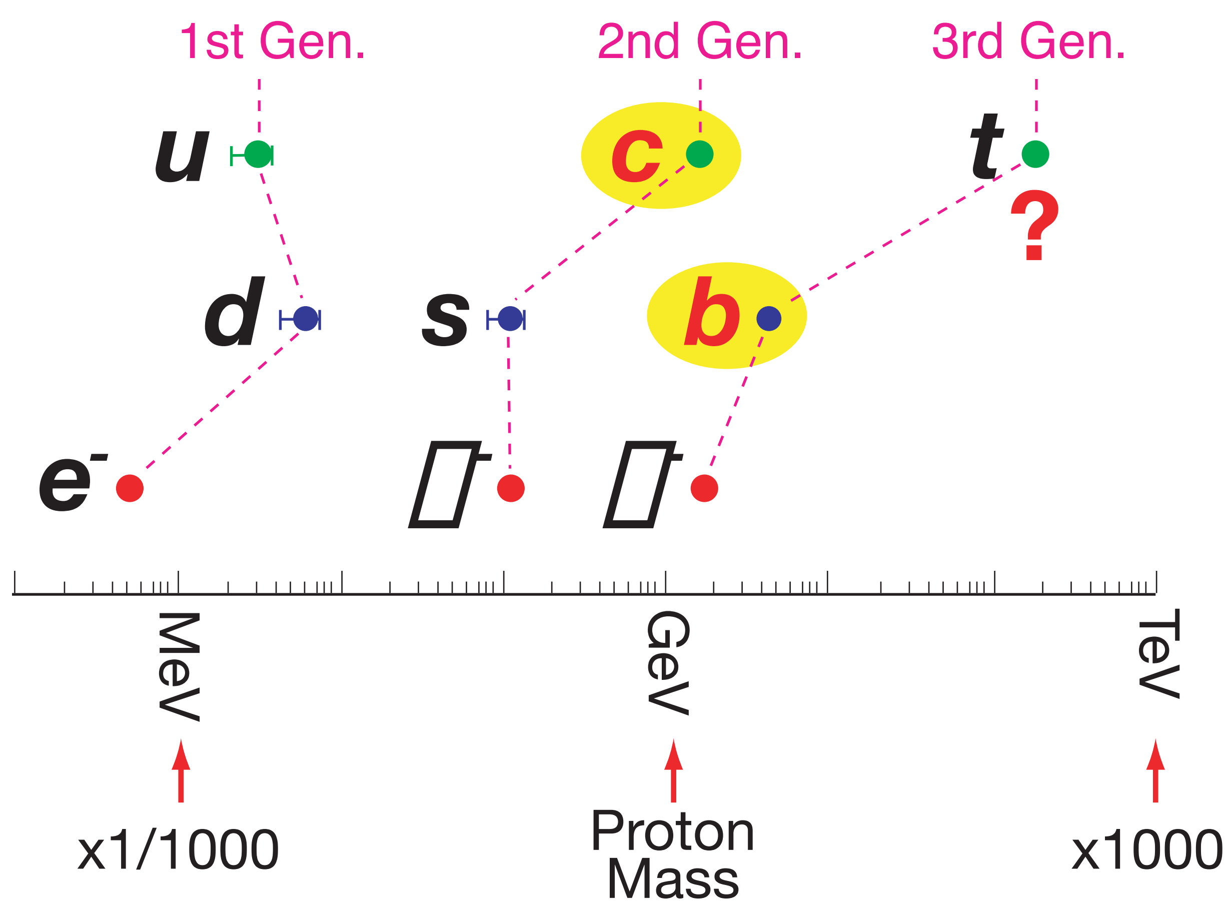
Flavor Physics

Mysterious mass "hierarchy"



Electroweak symmetry breaking
may explain *how* particles acquire mass,
but says nothing about *what* the masses are

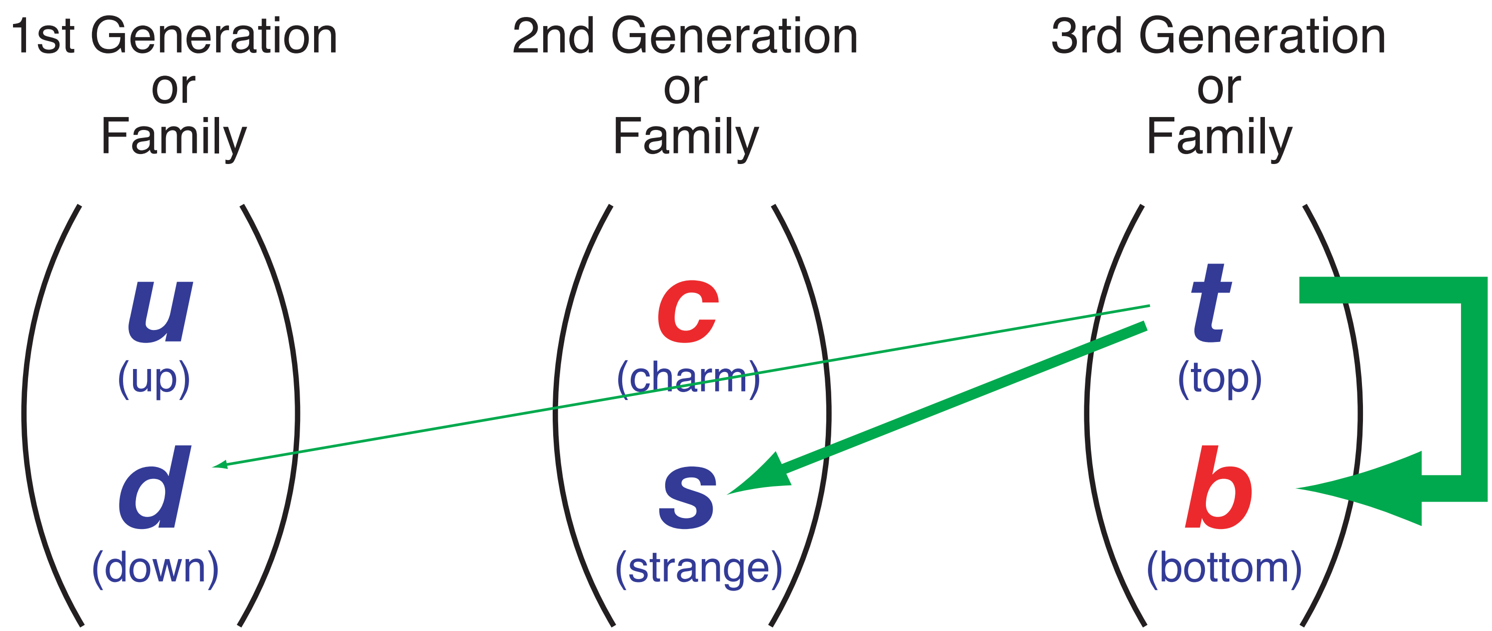
Heavy Flavor Physics



Heavy flavor quark physics:
b and *c* quarks are most massive
quarks that can comprise *observable* particles
+ can often make more precise theoretical predictions ("perturbative")

Heavy Flavor Physics

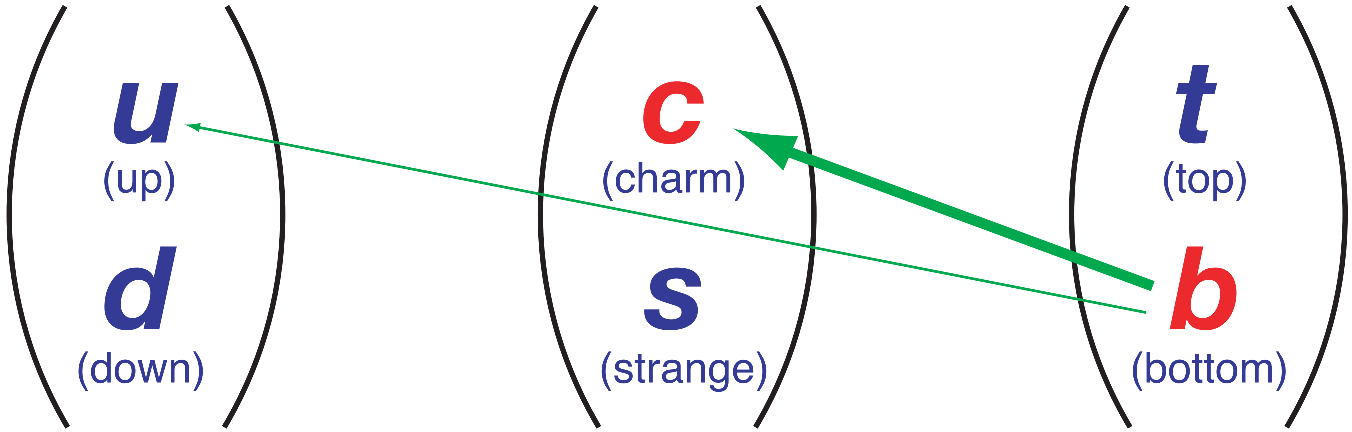
How flavor changes → coupling strengths



Heavy Flavor Physics

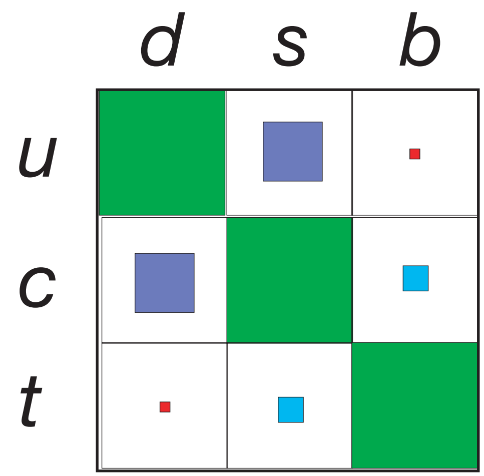
How flavor changes → coupling strengths

1st Generation 2nd Generation 3rd Generation

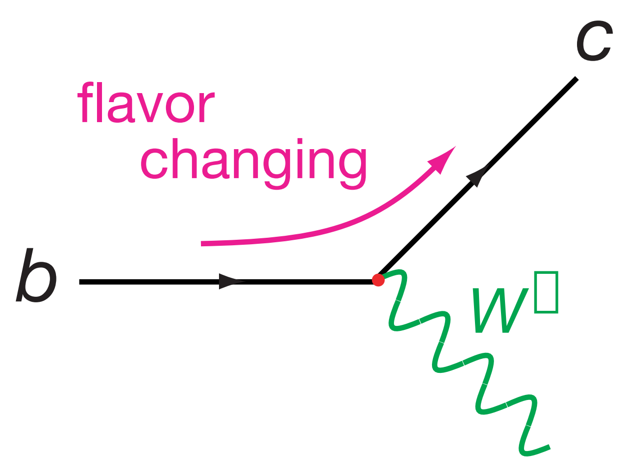


Kobayashi & Maskawa
1/2 of 2008 Nobel Prize

(broken symmetry
in this framework
explored by Tevatron)

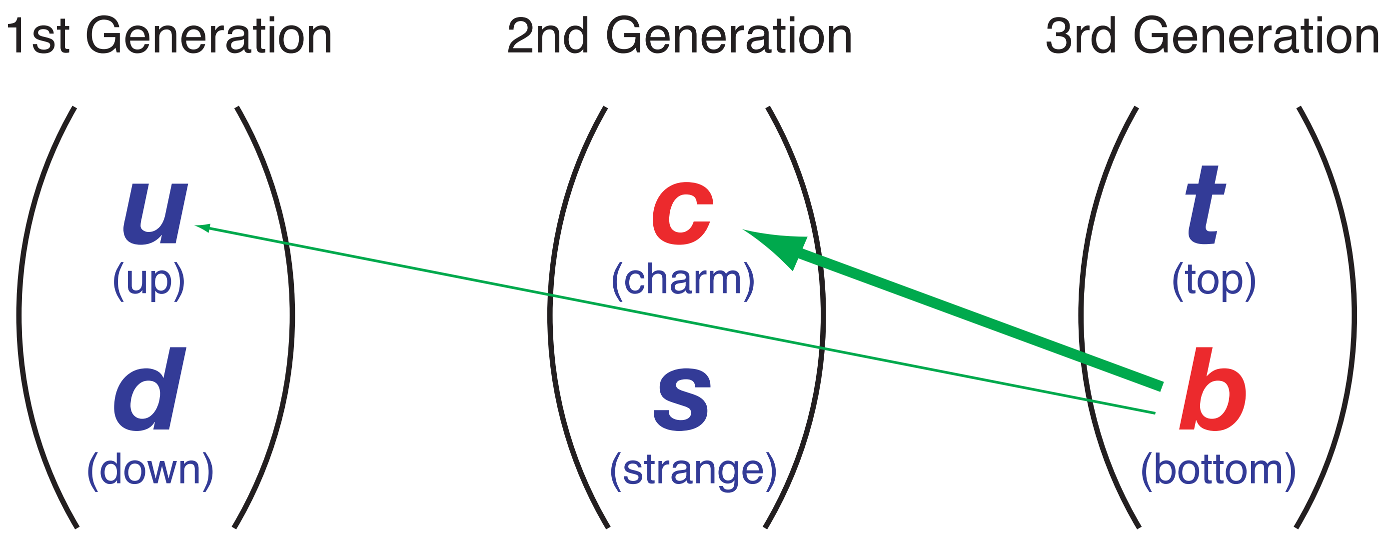


"CKM Matrix": values measured:
don't know why such a pattern

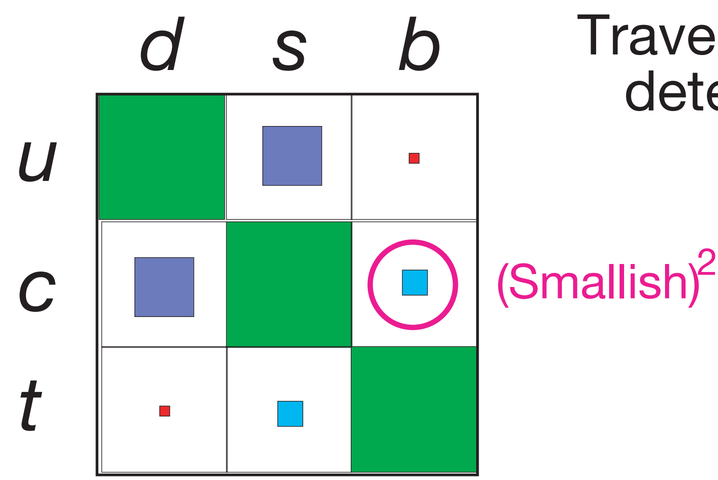


Heavy Flavor Physics

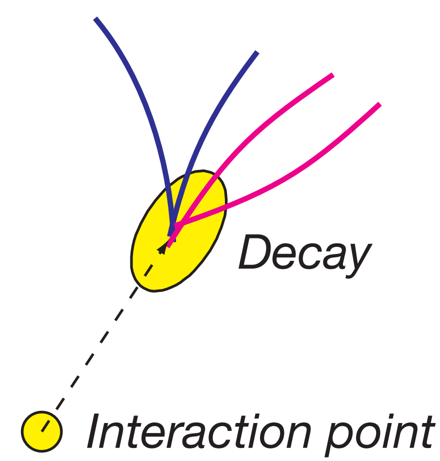
How flavor changes → coupling strengths



"Goldilocks" particles:
not too light,
not too heavy



Travels few mm's in
detectors, observable!

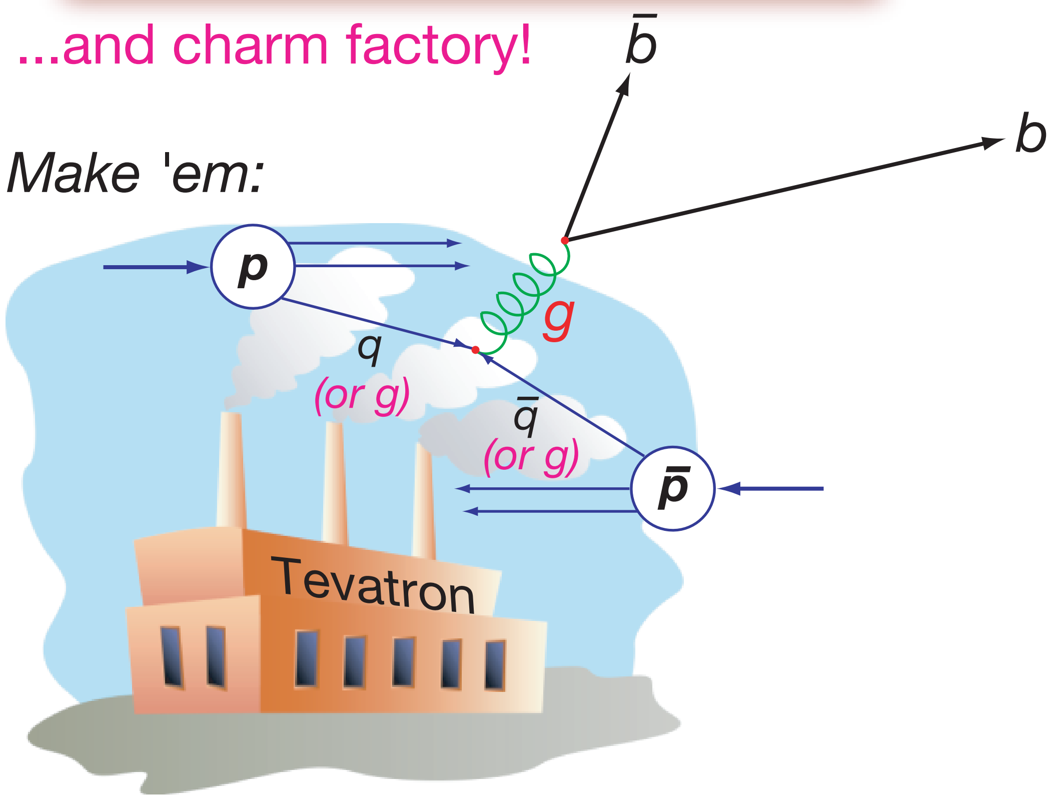


Tevatron as a *B* Factory

Use all that energy & intensity for copious *b/c* quark production!

...and charm factory!

Make 'em:



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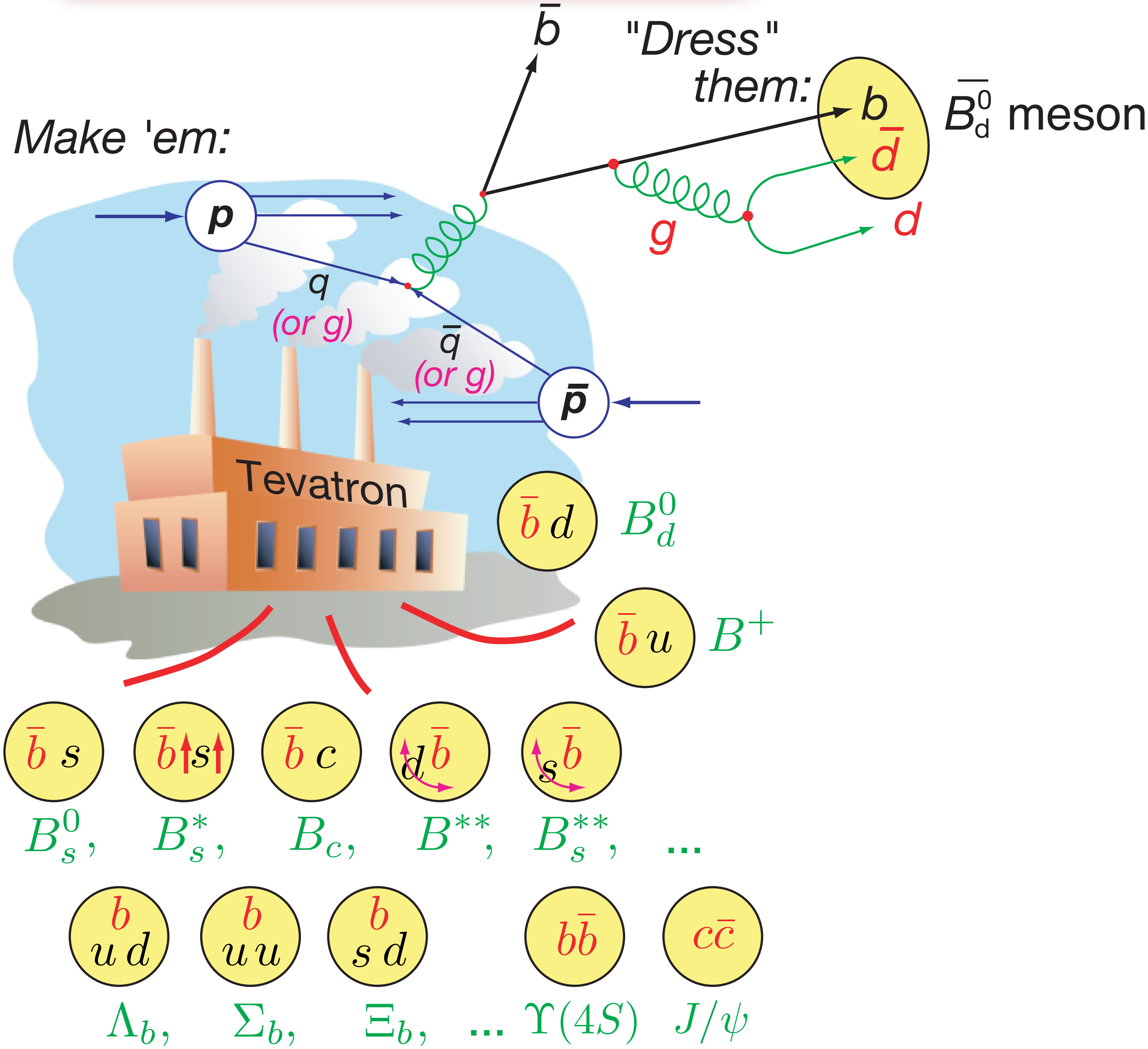

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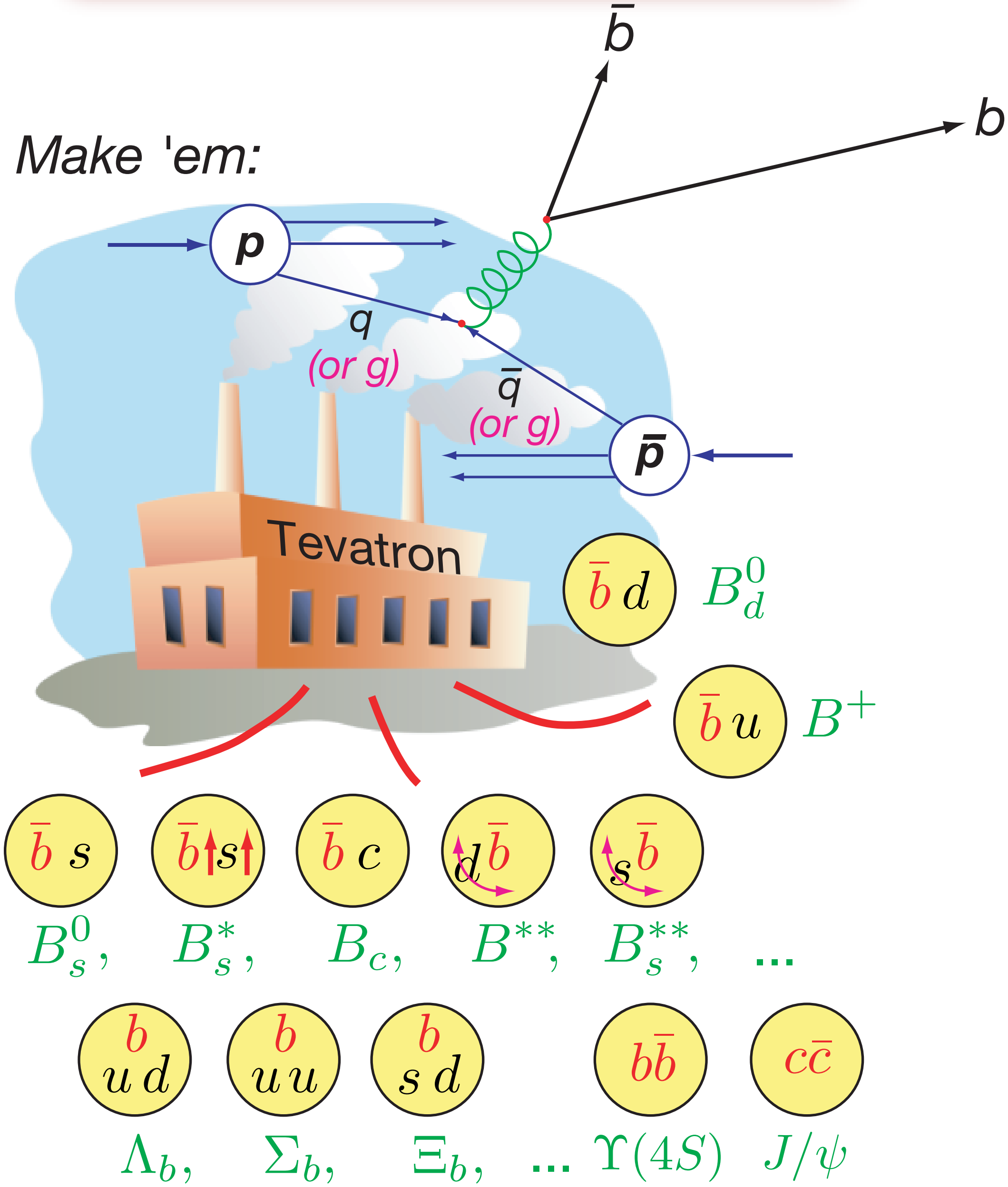
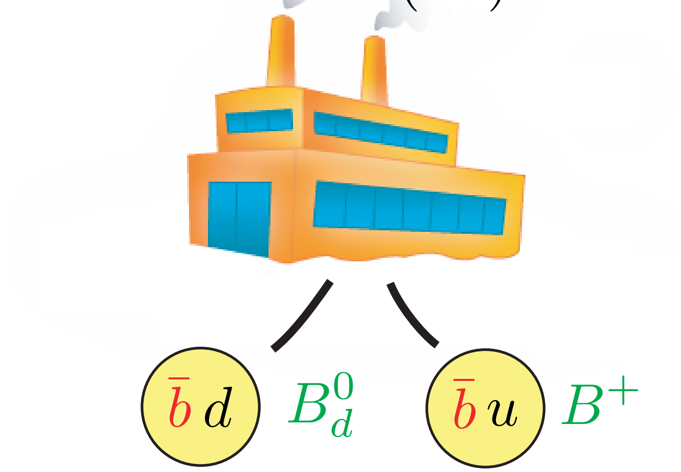


The other *B* factories:
CESR (Cornell),
KEKB (Japan),
PEP II (SLAC)

$$e^+e^- \to \Upsilon(4S) \to b\bar{b}$$



...asymmetric *B* factories proposed by Pier Oddone in 1987...

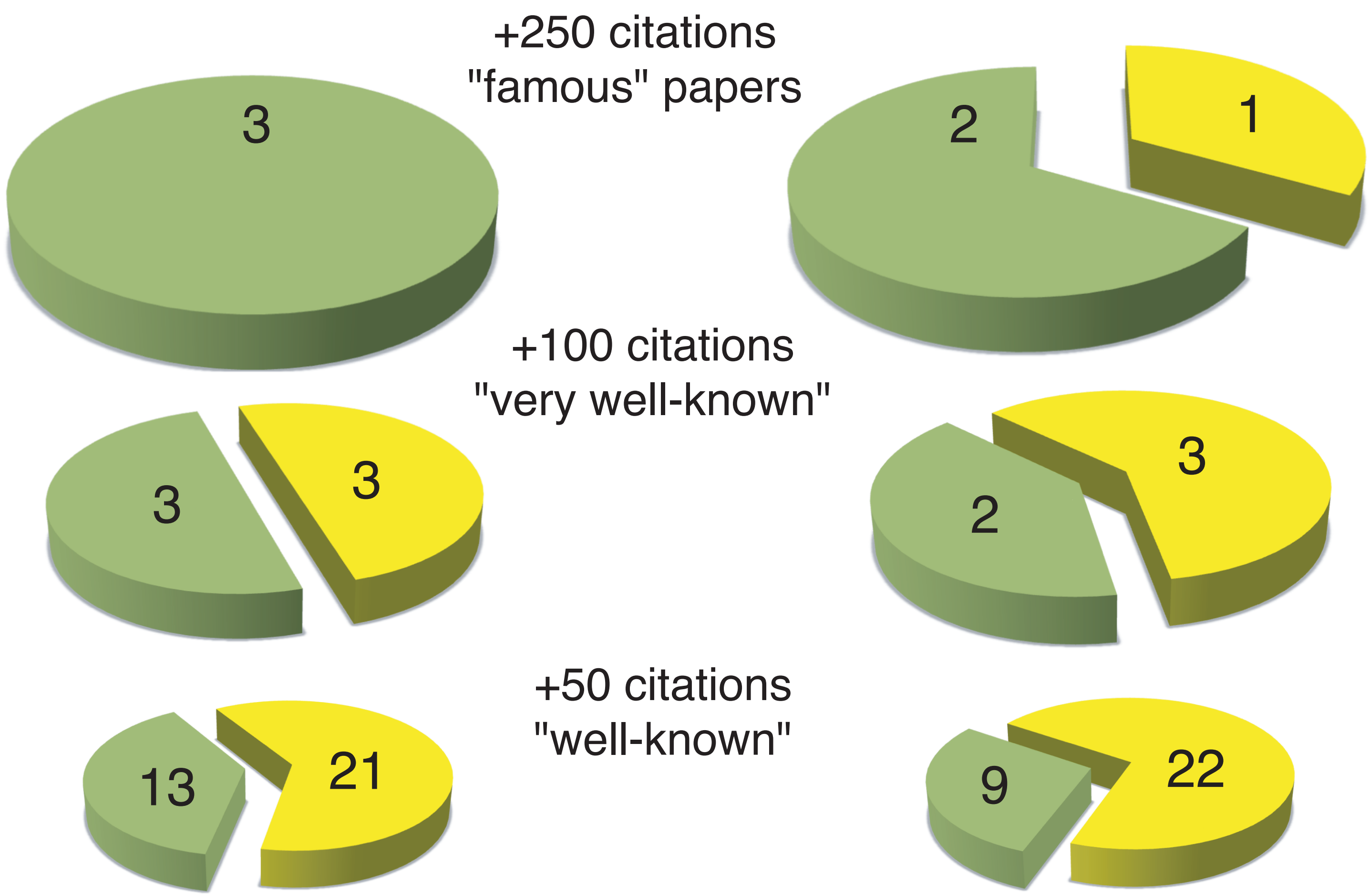
Heavy Flavor Program

...has been big part of the Tevatron physics program (and high impact!)

Number of published & submitted Run II publications:

CDF: 216 + 59 HF

DØ: 173 + 41 HF



Tevatron Run 1/Run 2

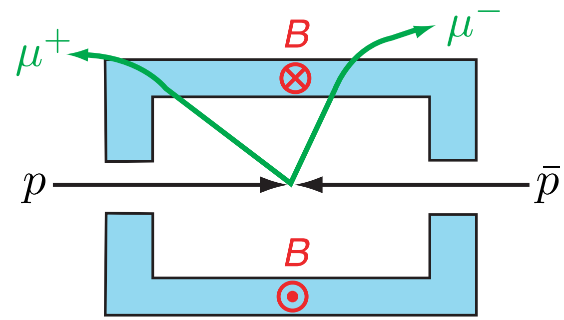
Evolution

Run 1 CDF: solenoidal *B* field, charged tracking, vertex TPC

(see Luciano's talk)

DØ: tracking (+vertexing), but only toroidal *B* field for muons

→ limits heavy flavor studies



Can a hadron collider really do heavy flavor/B physics?

Tevatron Run 1/Run 2

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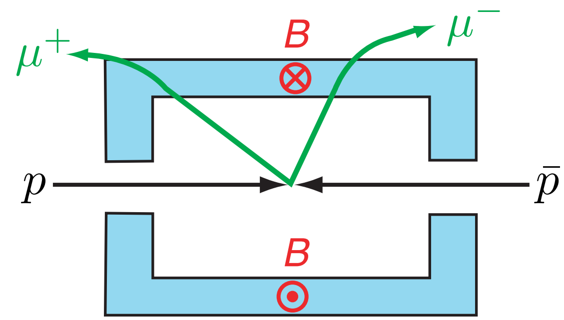

Can a hadron collider really do heavy flavor/B physics?

YES! Demonstrated by CDF!

surprising, e.g., LEP ($e^+e^- \to Z^0 \to b\bar{b}$)
with their capabilities

Tevatron Run 1/Run 2

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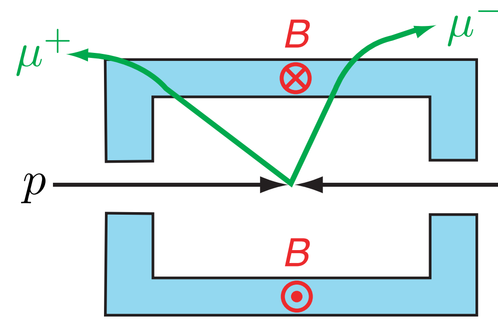
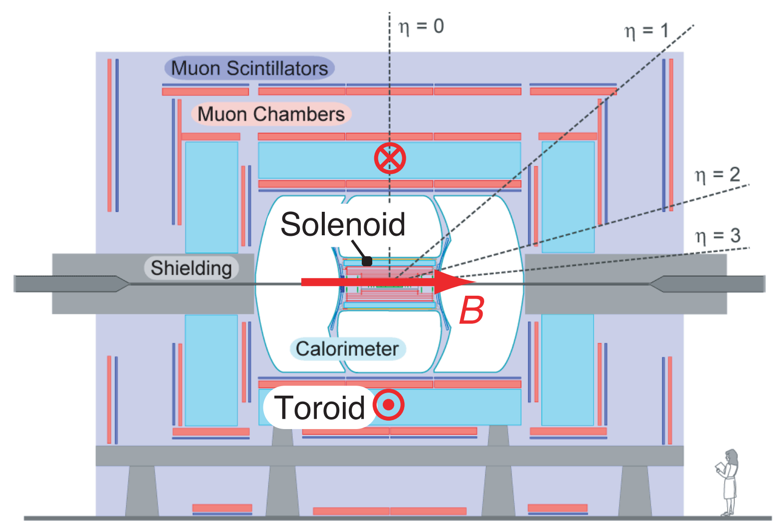


Run 2 *Upgrade detectors!*

CDF: (see Luciano's talk)

DØ: add solenoid, central fiber tracker, silicon microvertex (Layer 0, Run 2b)

→ joins the fun!



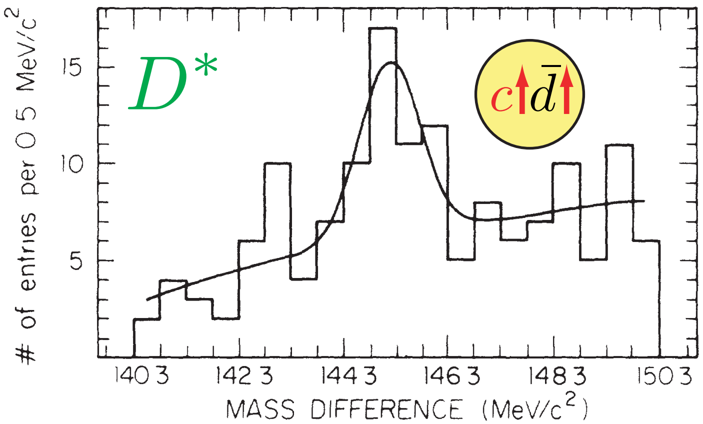
~25 years of progress

Statistics + resolution

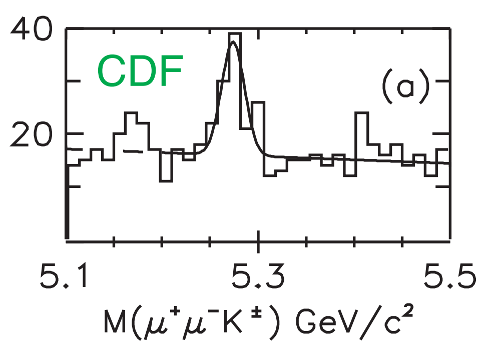
First (publish.) heavy flavor:

CDF: Phys. Rev. Lett. **64**, 348 (1990)

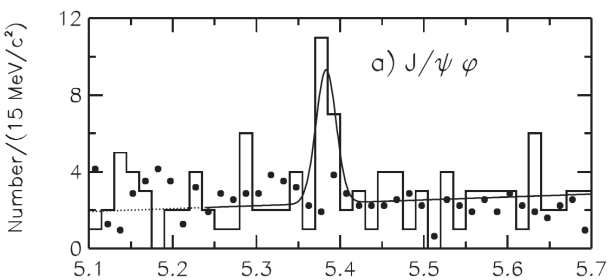
D^* $c\bar{d}$



B^+ $\bar{b}\,u$



B_s^0 $\bar{b}\;s$



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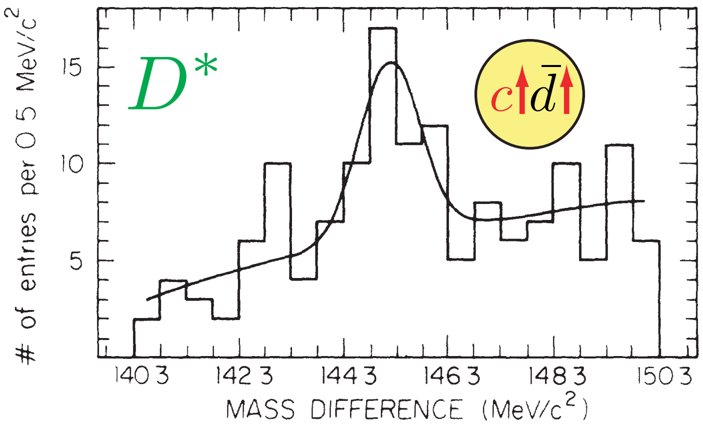
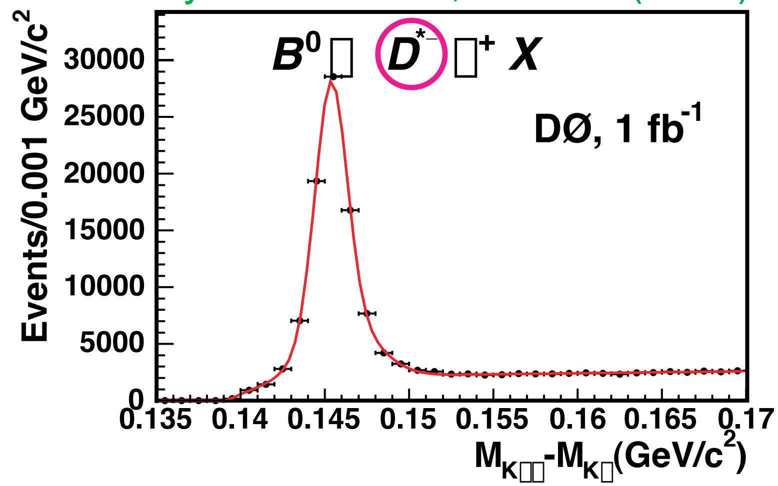
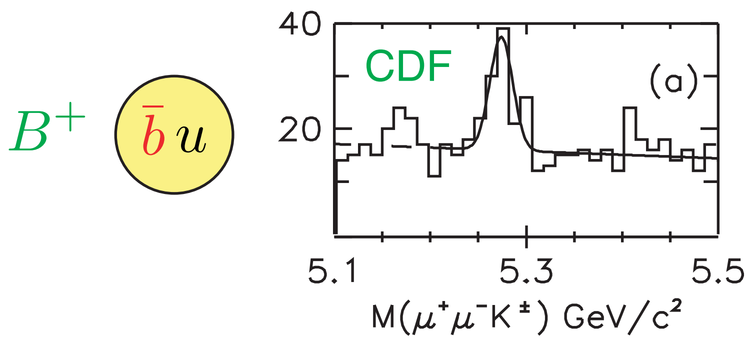
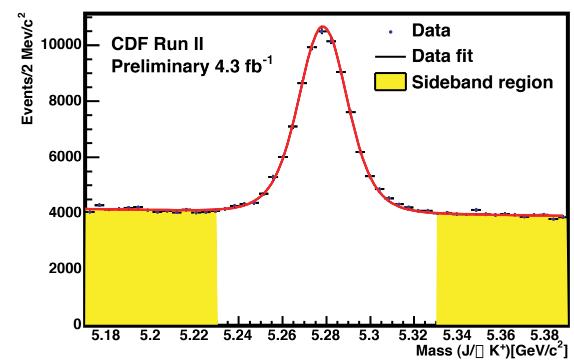
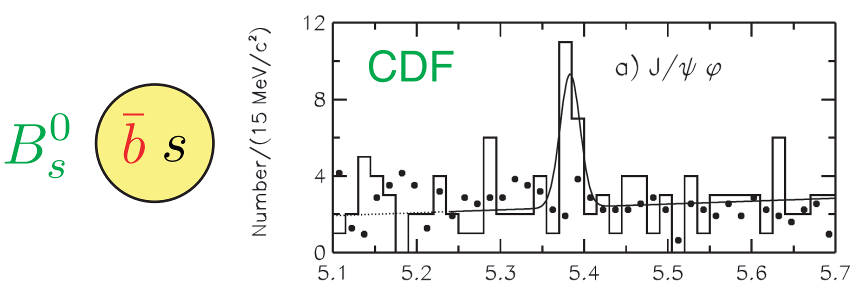


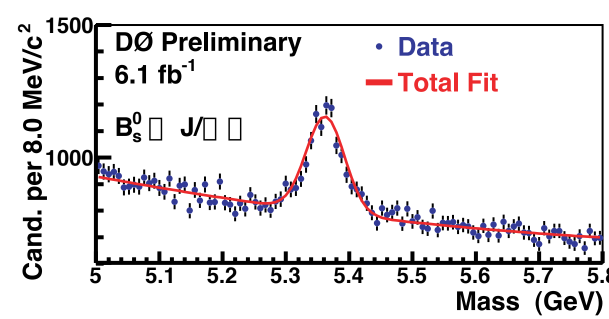
DØ: Phys. Rev. D **74** , 112002 (2006)









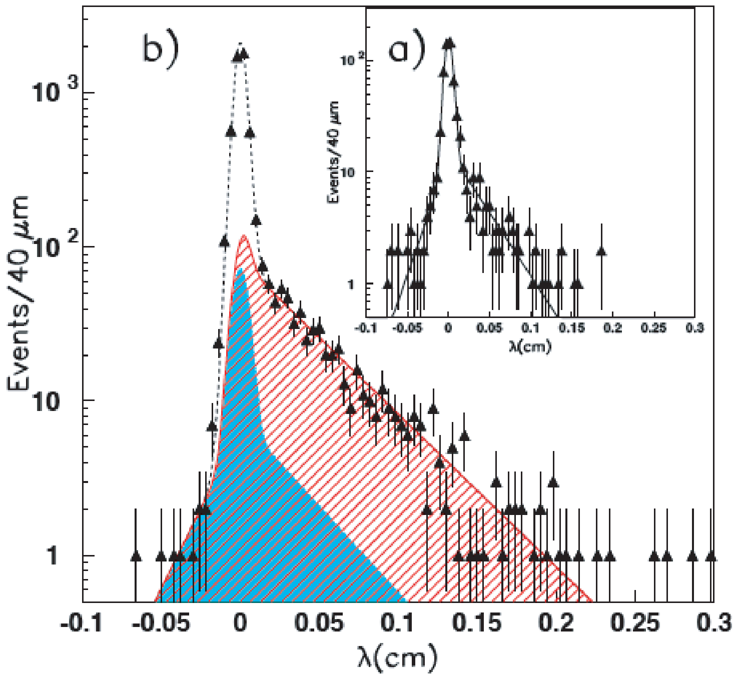


~25 years of progress

Statistics + resolution

Properties, e.g., lifetimes:

CDF, Phys. Rev. Lett. **71**, 3421 (1993).



Lumping all *B* hadrons together

~25 years of progress

Statistics + resolution

Properties, e.g., lifetimes:

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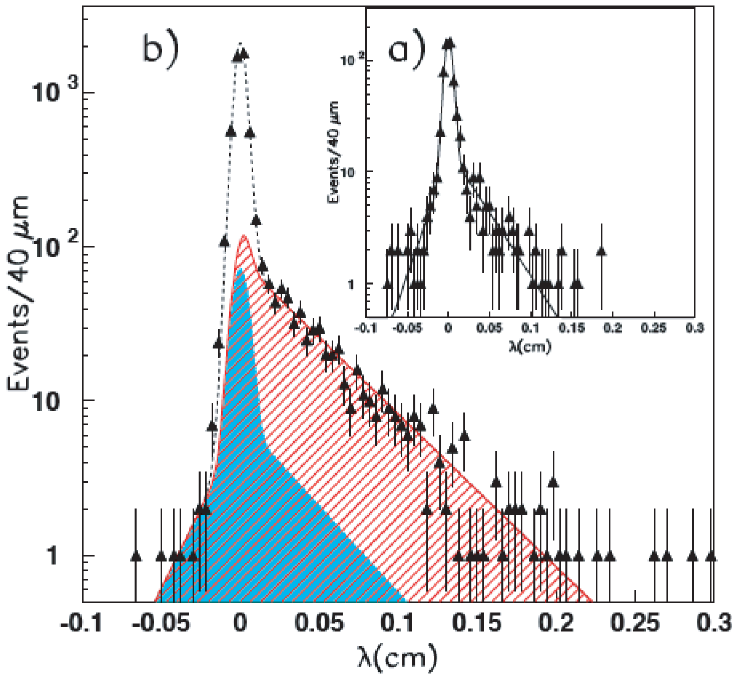
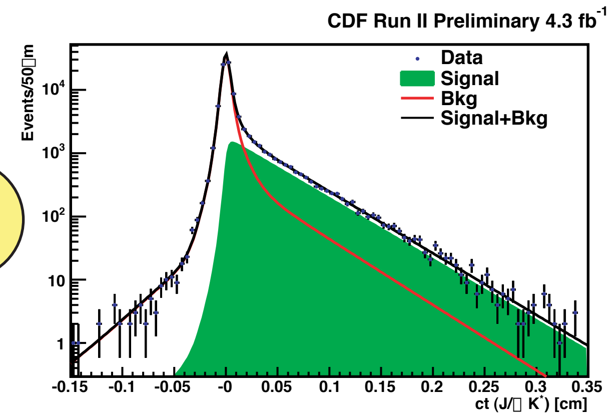
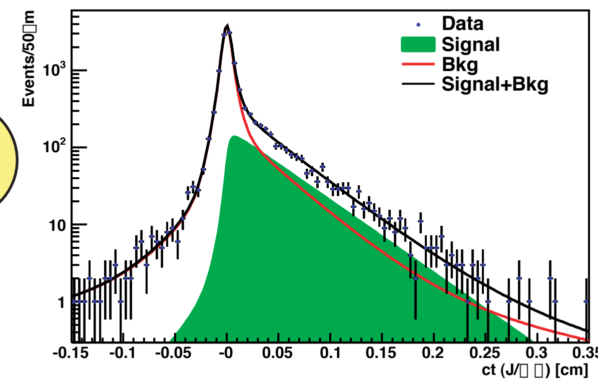


Lumping all *B* hadrons together

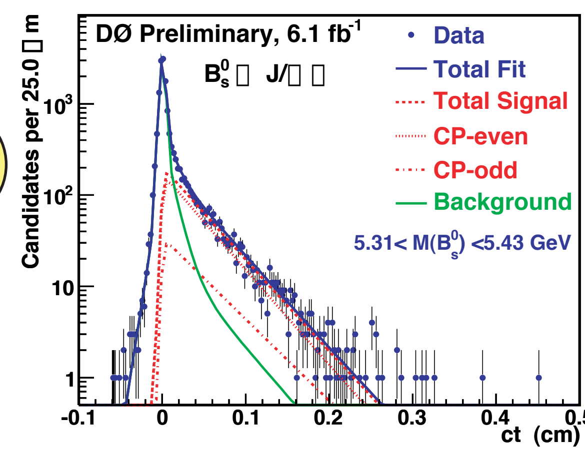
B^+ $\bar{b}\,u$



Λ_b $b\,u\,d$



B_s^0 $\bar{b}\,s$

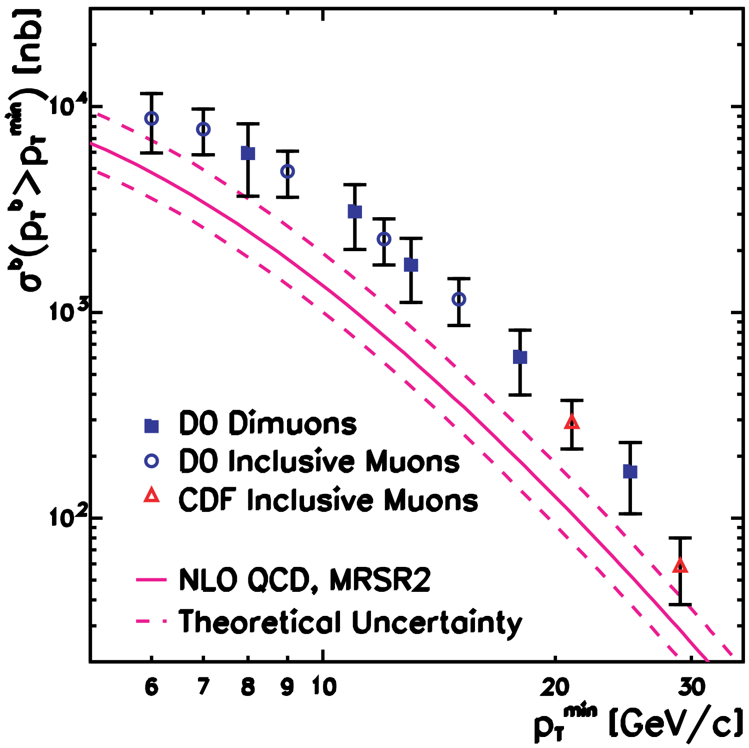


World's most precise...

The Strong: Heavy Flavor Production

Heavy quarks provide excellent QCD laboratory,
early discrepancies:

Run 1

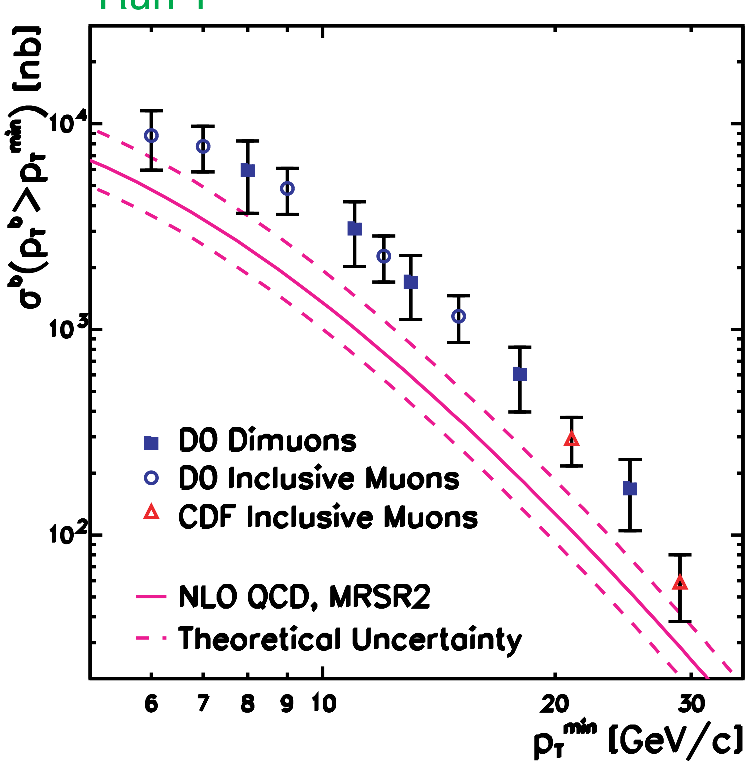


The Strong: Heavy Flavor Production

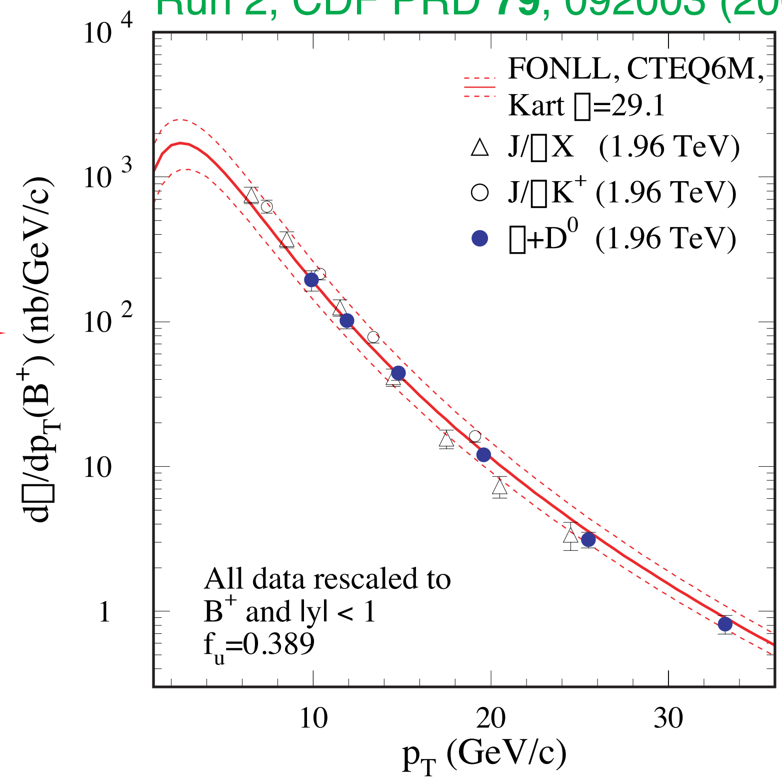
Incremental Progress

Heavy quarks provide excellent QCD laboratory,
early discrepancies:

Run 1



Run 2, CDF PRD **79**, 092003 (2009)



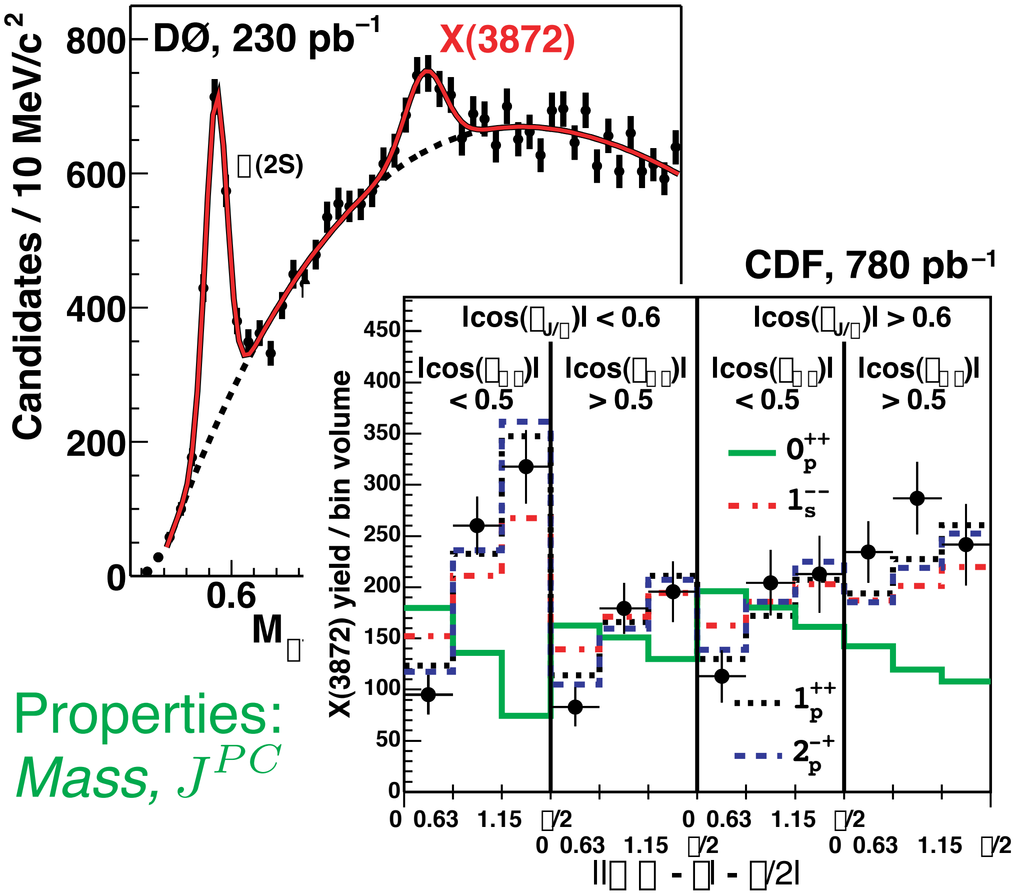
Sum of many *small* changes:

- gluon PDF, α_s
- *b* fragmentation function
- fixed order (NLO) & NLL theory
- pollution w/ other production modes

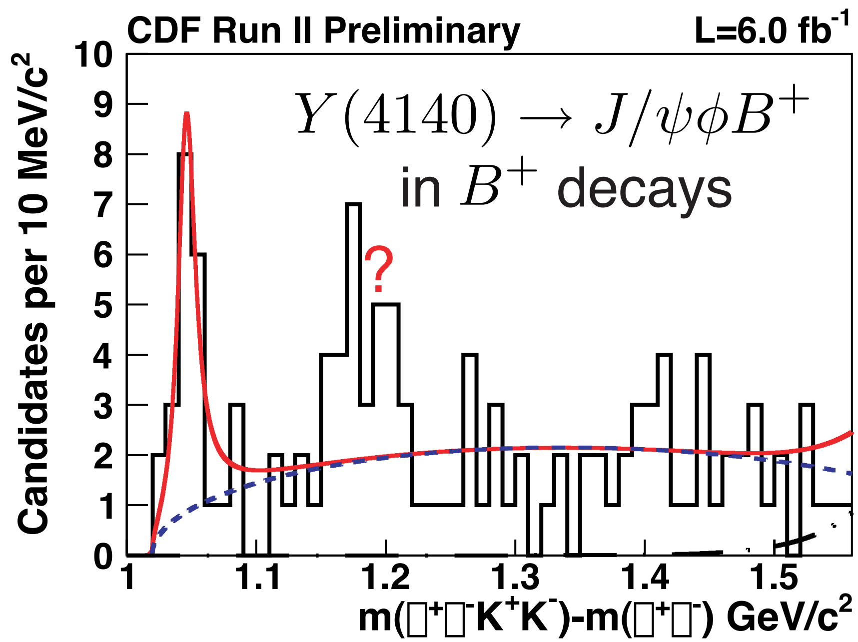
The Puzzling: New States of Matter?

Renaissance of Spectroscopy

- *X*(3872) discovered at Belle, also observed at Tevatron



- *Y*(4140) discovered at CDF



Properties:
Mass, J^{PC}

$c\bar{c}u\bar{u}$

?

$(c\bar{u})(\bar{c}u)$

$D^0\ \bar{D}^{*0}$

"Molecules"

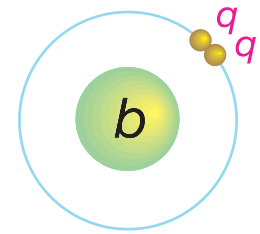
?

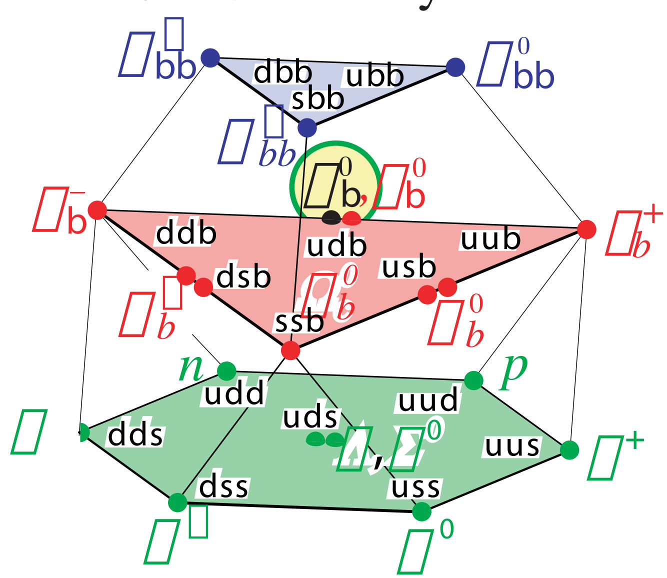
$(c\bar{s})(\bar{c}s)$

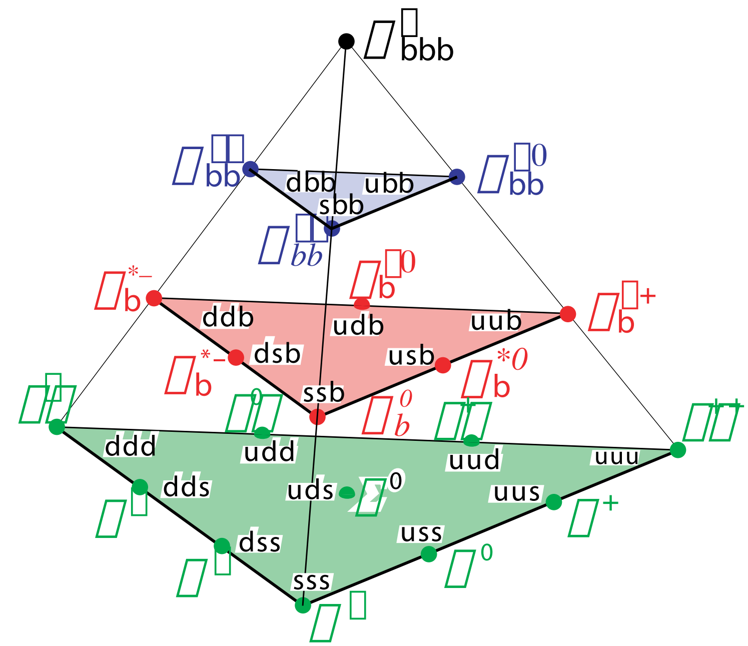
$D_s^*\ \bar{D}_s^*$

The New: Grab Bag of Quarks

Renaissance of Spectroscopy





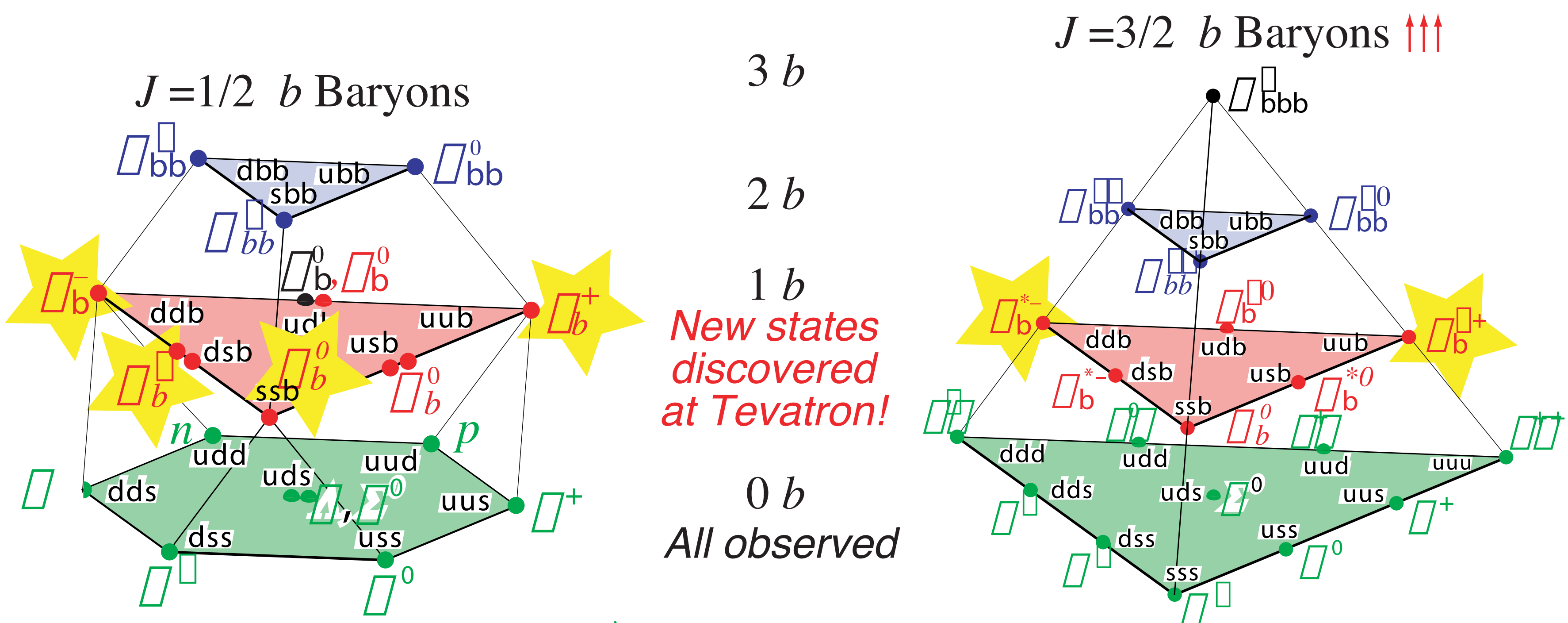


- Until Tevatron, ground state Λ_b was the only directly observed *b* baryon

$$\Lambda_b^0 = |bud\rangle$$ LEP

The New: Grab Bag of Quarks

Too many peaks to show...
(new charm baryon and excited mesonic states too)



- Until Tevatron, ground state Λ_b was the only directly observed *b* baryon

$\Lambda_b^0 = |bud\rangle$ LEP, DØ, CDF

Strongly decaying, different spin alignments: $\Sigma_b^{\pm} = |bqq\rangle, q = u, d$ CDF

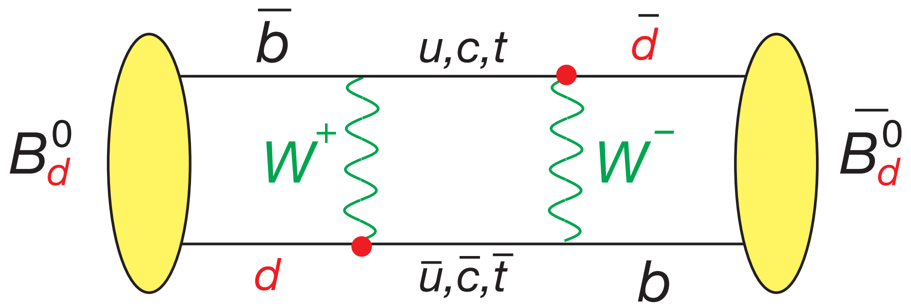
Discovered week apart,"Triple-scoop baryon": $\Xi_b^- = |bsd\rangle$ DØ, CDF

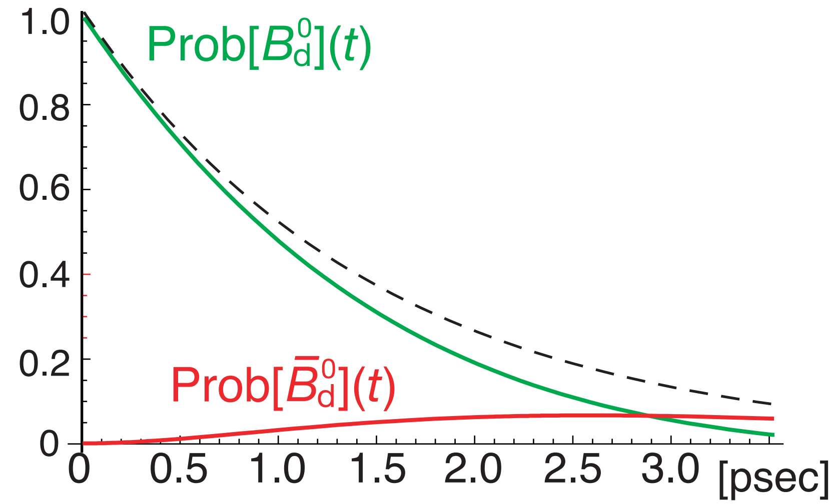
Doubly-strange *b* baryon, mass discrepancy: $\Omega_b^- = |bss\rangle$ DØ, CDF

The Quick: B_s^0 Oscillations

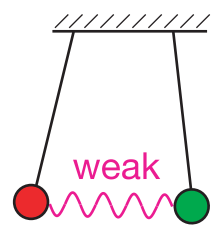
Turning a particle to an anti-particle

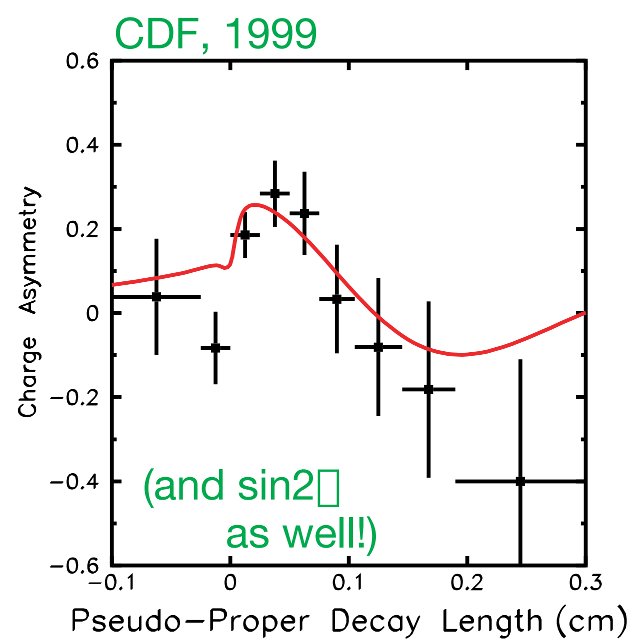
Prelude: not so quick



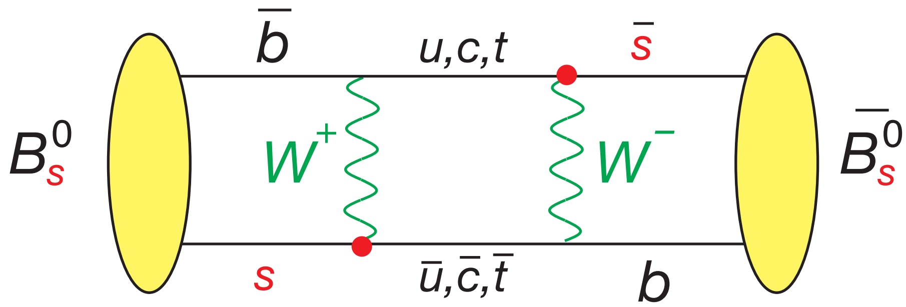


Think coupled pendula!

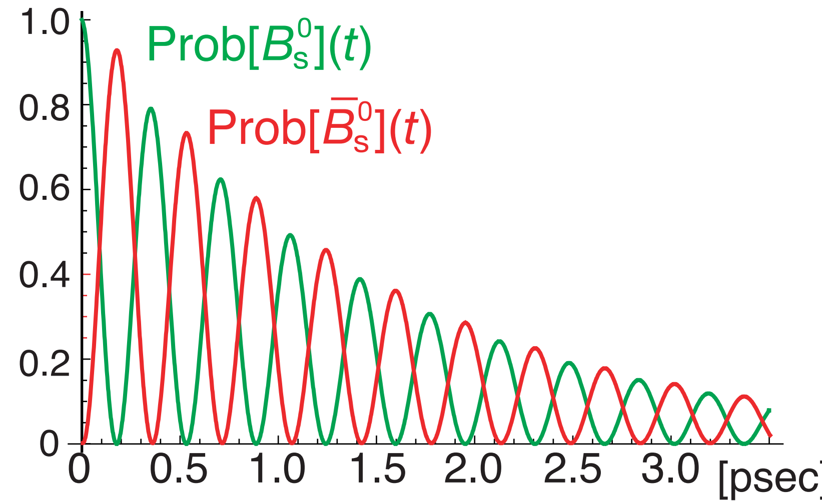




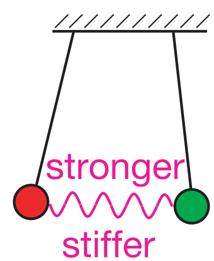
The Quick: B_s^0 Oscillations

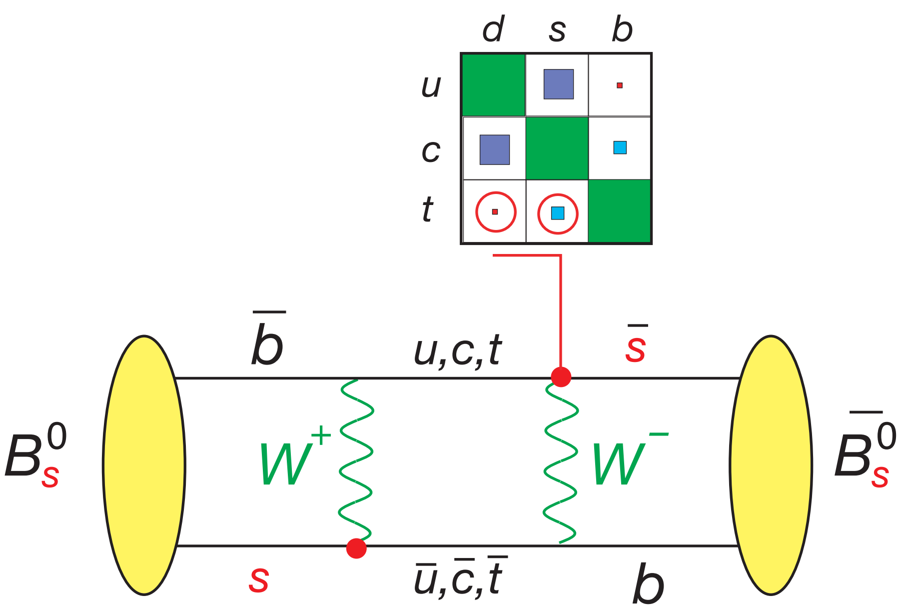


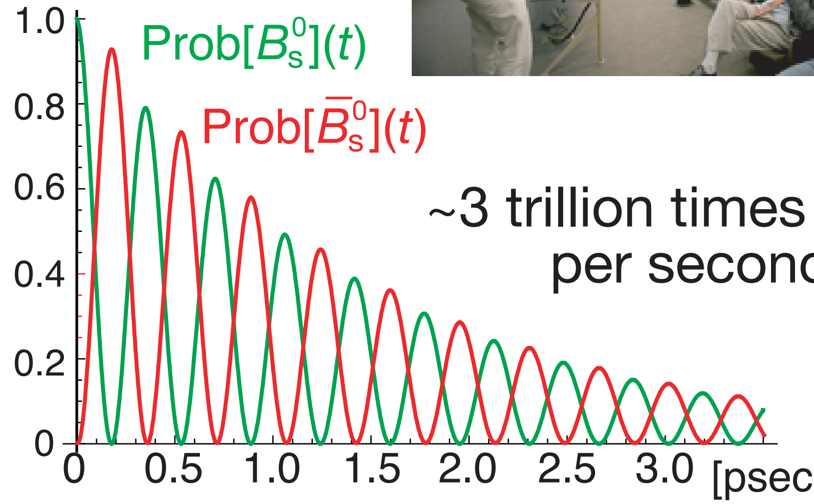
Turning a particle to an anti-particle (quickly)



Think coupled pendula!



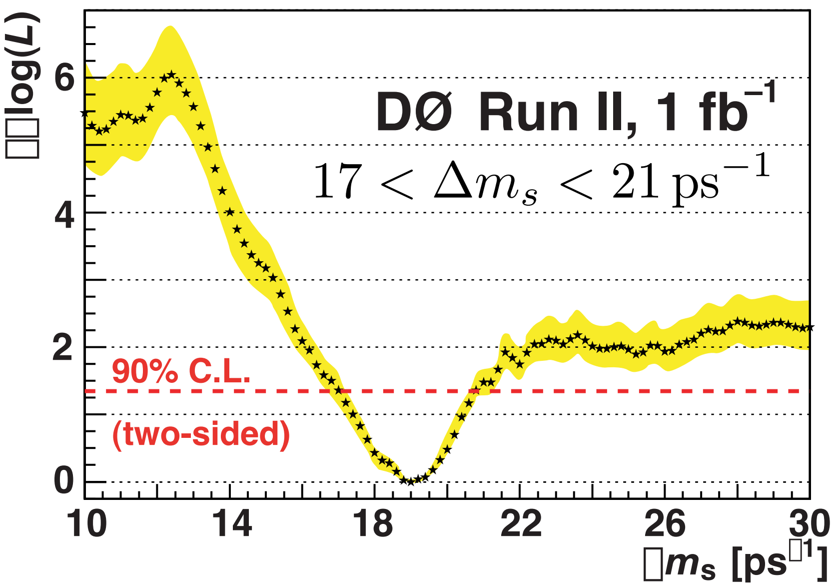




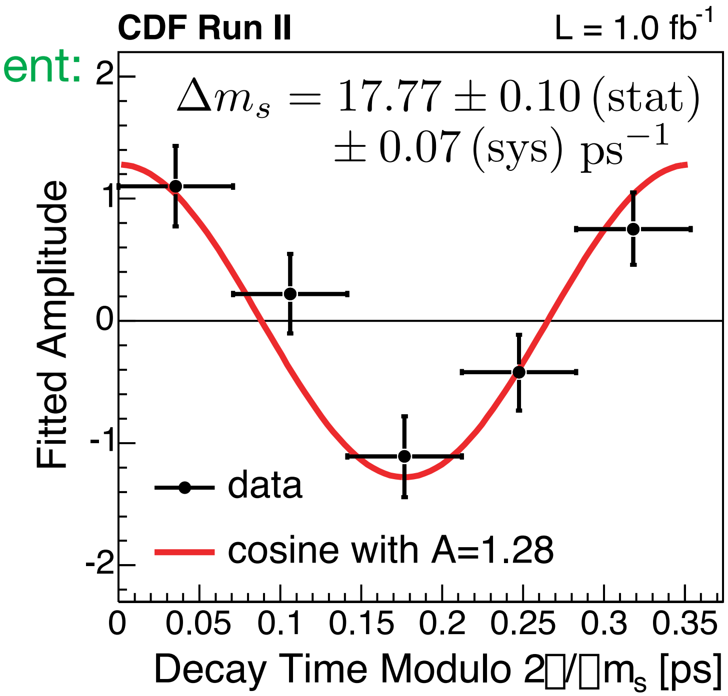
~3 trillion times per second!

A ~20 year quest to observe, starting at LEP! In 2006:

First two-sided limit:



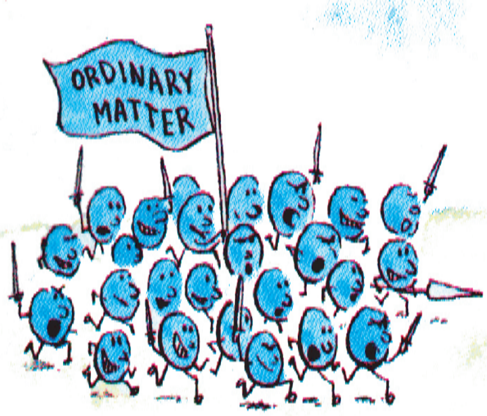
First measurement:



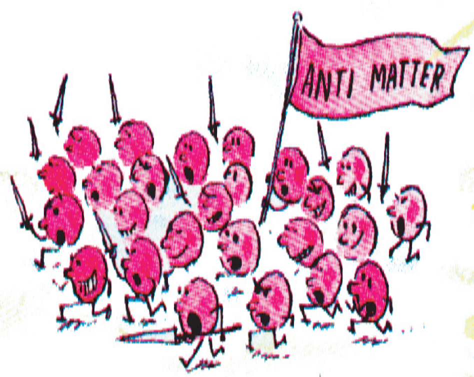
The Lopsided: *CP* Violation

Early universe, 10^{-35} sec,
quarks = # antiquarks,
but then:

due to CP violation
in time between 10^{-32} and 10^{-4} sec ...

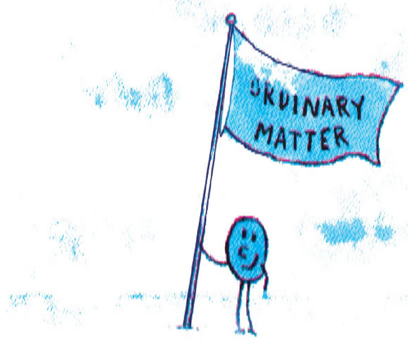


10,000,000,001



10,000,000,000

Last person standing



1
Us!

The Lopsided: *CP* Violation

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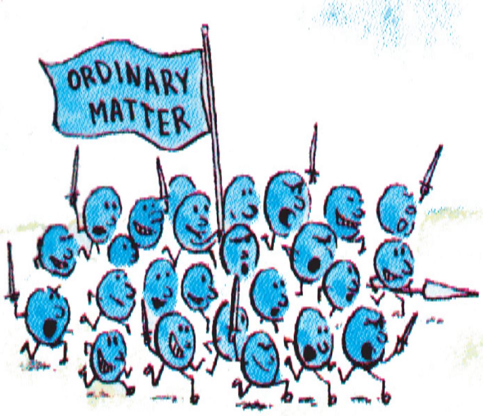
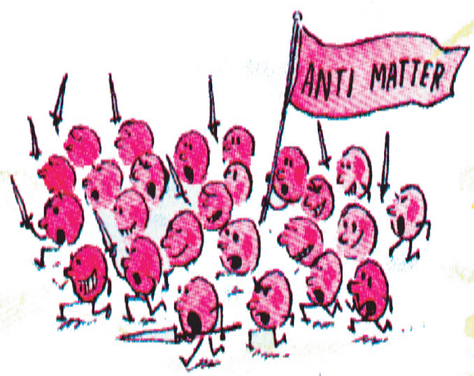
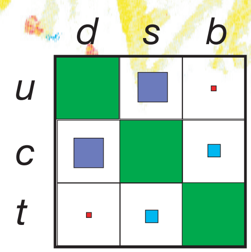




Last person
standing

1
Us!

10,000,000,001 10,000,000,000



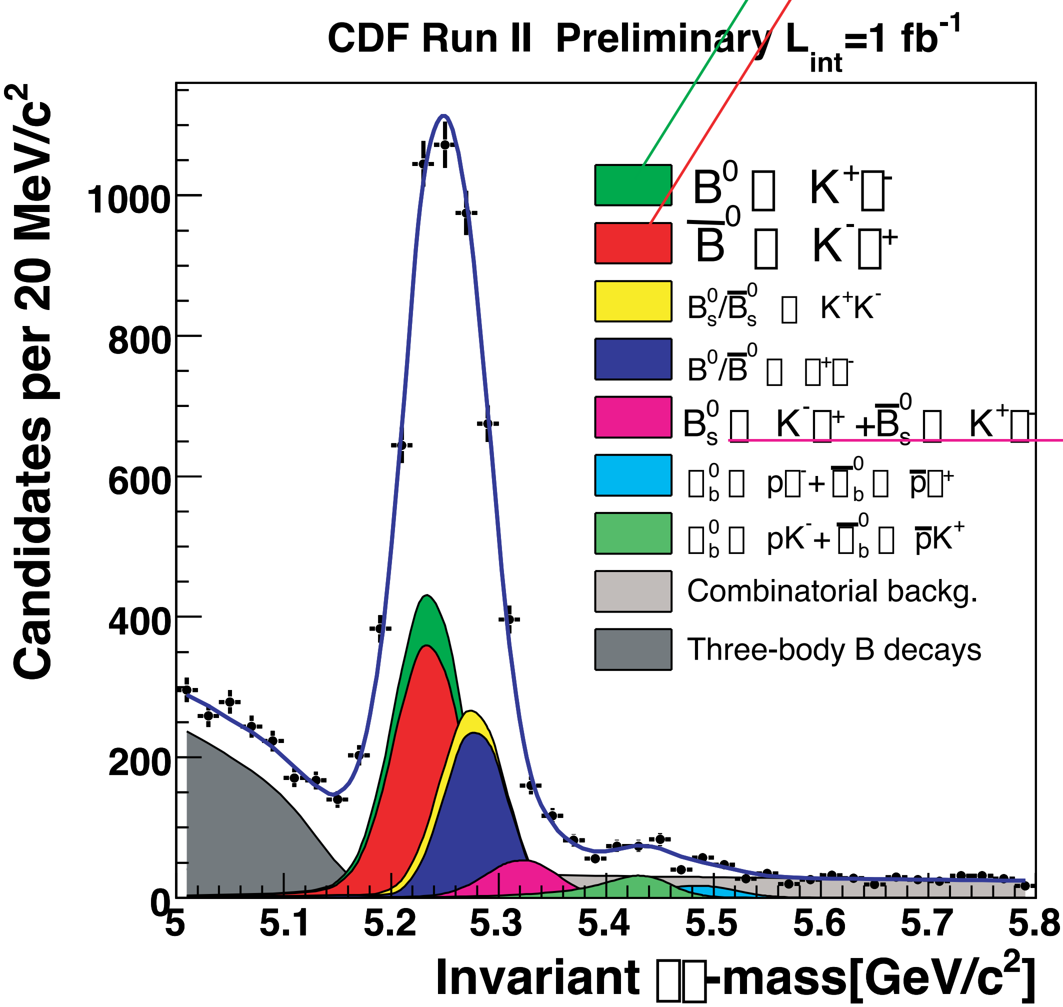
The SM source of CP violation is insufficient to explain the imbalance between matter and antimatter

The Lopsided: *CP* Violation

Directly in decay...

e.g., CDF: are the rates of $\begin{matrix} B^0 \to K^+\pi^- \\ \bar{B}^0 \to K^-\pi^+ \end{matrix}$ the same? ***No!***

Competitive w/ *B* factories,
agrees with SM



Only at Tevatron:

$$\mathcal{A}_{\rm CP}(B_s^0 \to K^-\pi^+)$$

Complementarity:

CDF two-track trigger essential
(can't do this at DØ)

The Lopsided: *CP* Violation

In mixing...

DØ: dimuon CP asymmetry; a matter – antimatter asymmetry

Direct semileptonic decay

Neutral *B* meson oscillation and then semileptonic decay

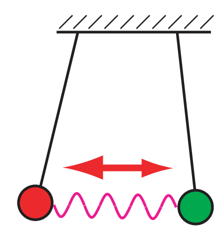
- Measure CP violation *in mixing* via

$$\boxed{A_{\rm sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = (-0.957 \pm 0.251\,({\rm stat}) \pm 0.146\,({\rm syst}))\%}$$

Number of same-sign $\mu^+\mu^+$ events

Number of same-sign $\mu^-\mu^-$ events

Back to coupled pendula



$$B^0 \to \bar{B}^0 \neq \bar{B}^0 \to B^0$$

From 1.5 billion single muon events
~4 million dimuon events

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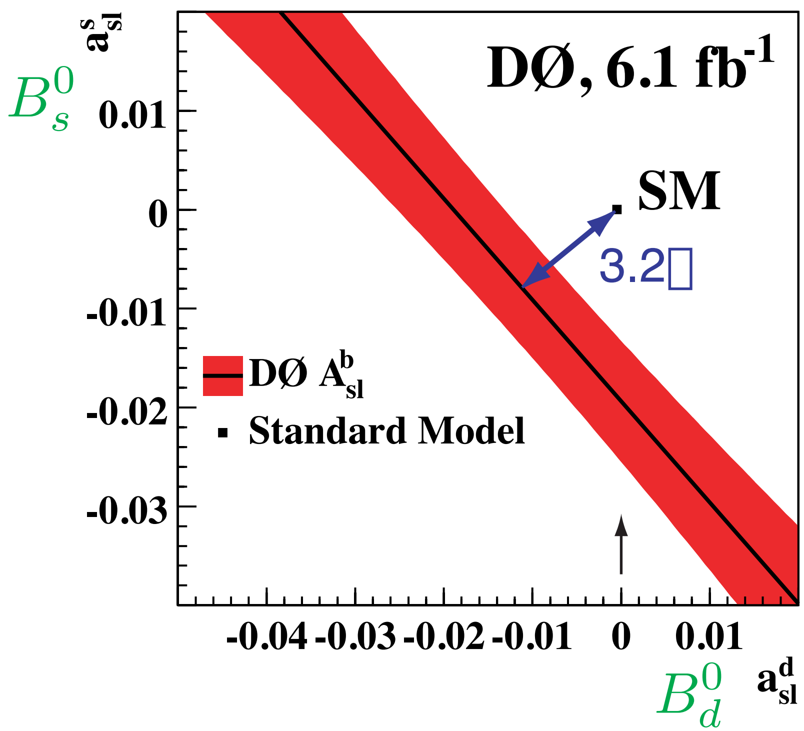
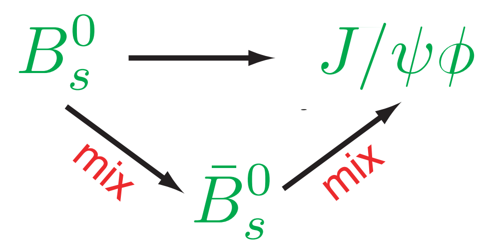


...and intriguing similar trends observed in B_s^0 system



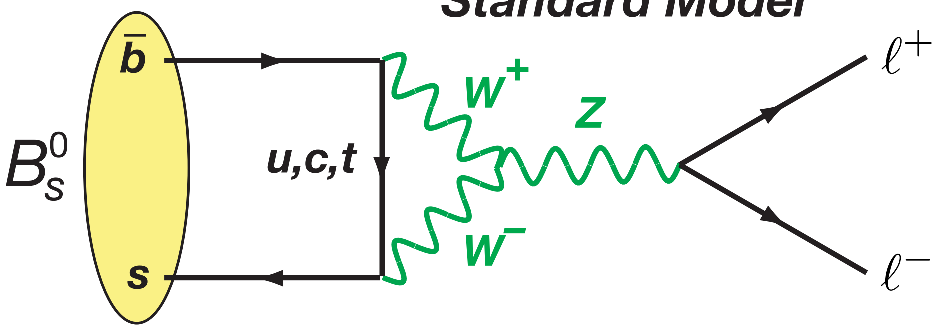
CP violation through *interference* of diagrams with and w/o mixing

Pointing to a new source of CP violation?

The Rare: Constraining New Physics

Including new more massive particles

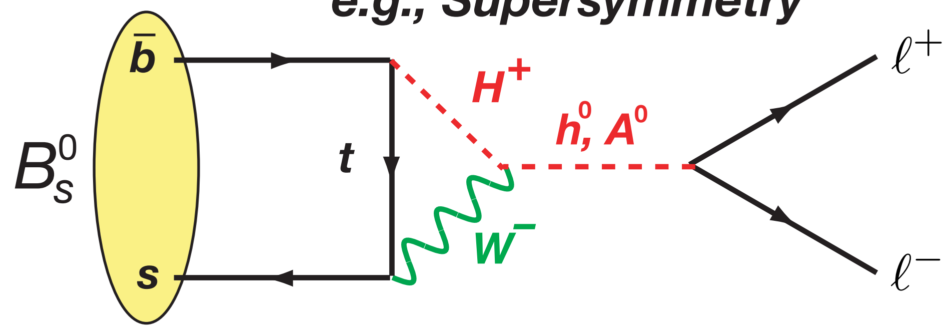
Standard Model



Predicted to be tiny

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \approx 3 \times 10^{-9}$$

e.g., Supersymmetry



Can make larger!

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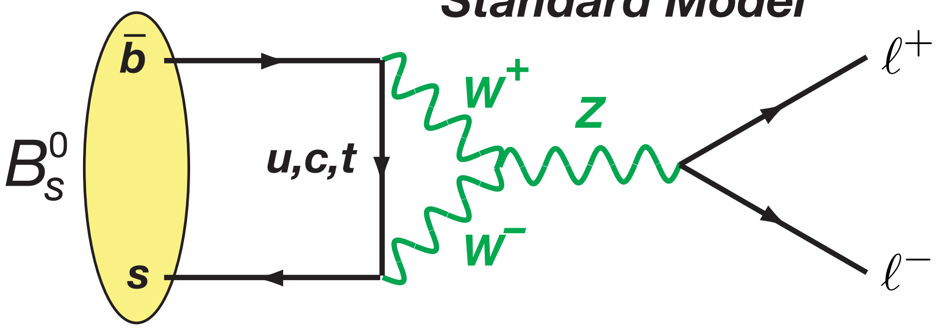

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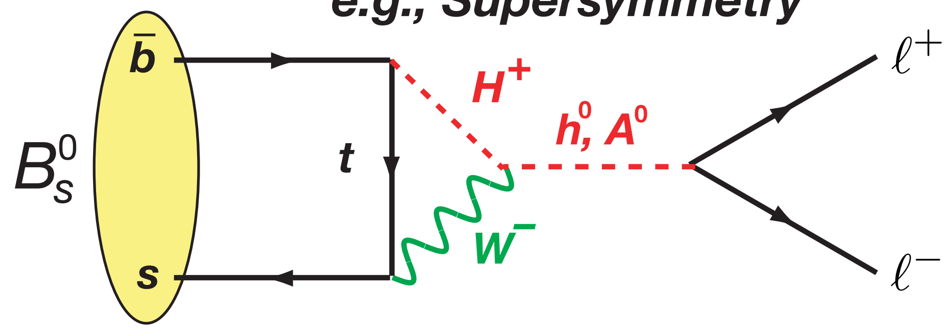

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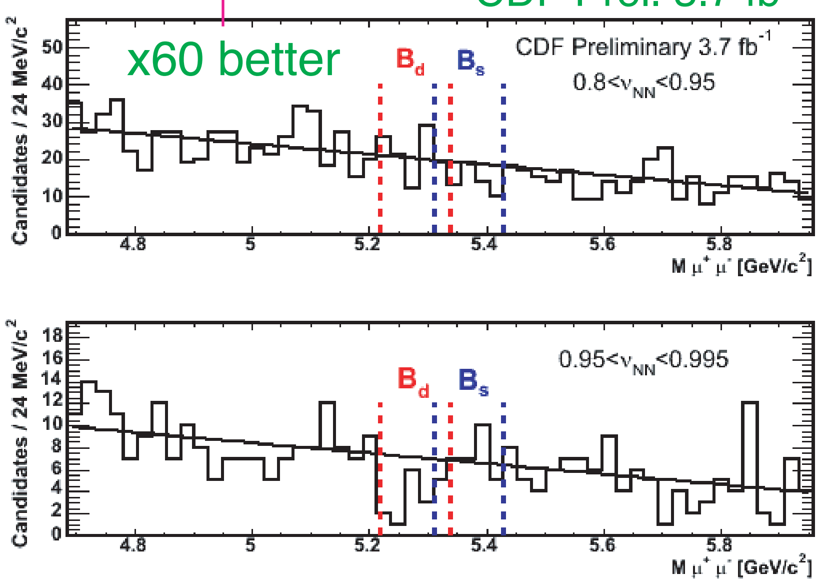
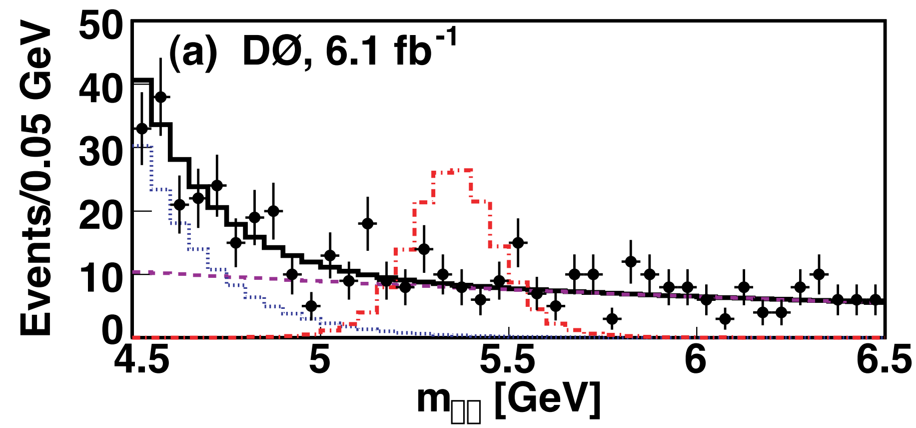
Starting in 1995 (CDF), keep searching!

CDF Prel. 3.7 fb^{-1}



Place limits,
"squeezing" new physics
(currently at ~x12 SM)



Conclusions & Prospects

Tremendously successful and exciting Heavy Flavor program at the Tevatron over the past decades

→ clearly demonstrated that it is possible to do this cutting-edge physics at a hadron collider *in addition* to the high p_T program

Important milestones achieved (e.g., measuring B_s oscillations), new states discovered, CKM matrix probed, new physics constrained

Very few systematics-limited analysis

→ will make full use of full dataset (including possible extension!!)

Seeing first hints of new physics (e.g., CP violation)? Brink of discovery?

Eagerly anticipating ATLAS, CMS, LHCb as they join the game!

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Low-luminosity "sweet spot"

Conclusions & Prospects

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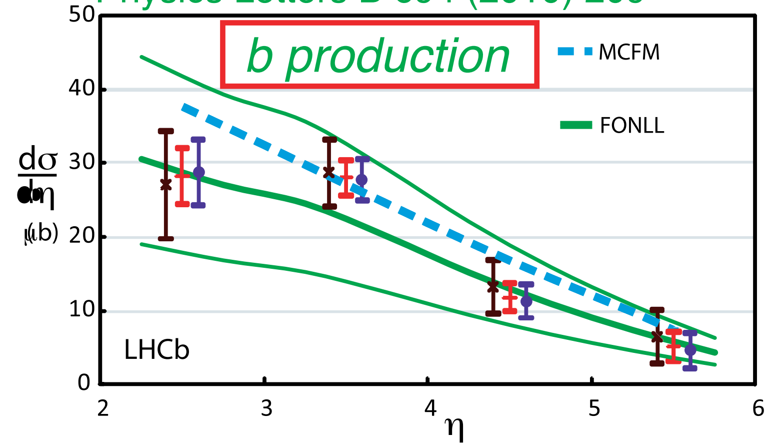
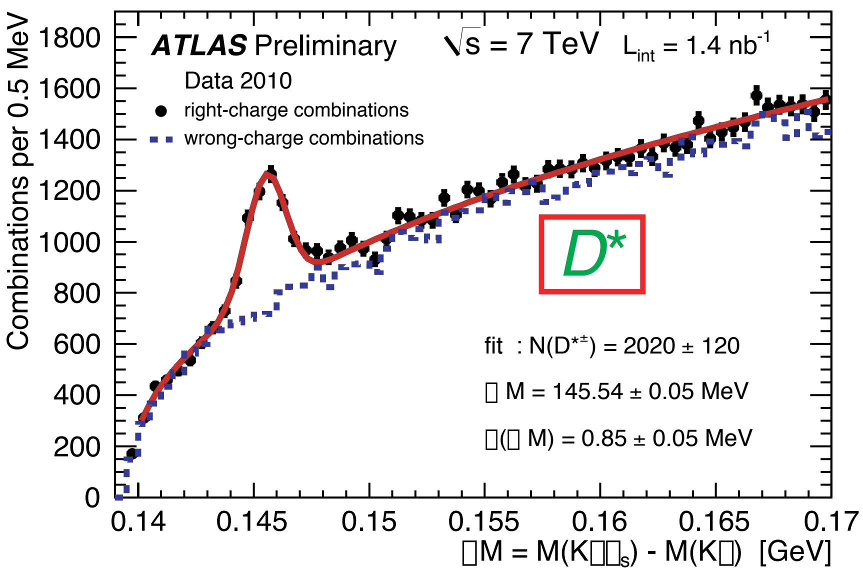
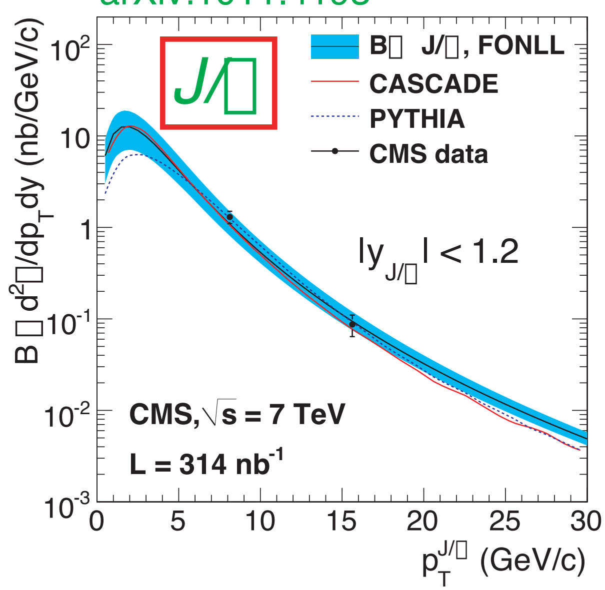


...and it begins again!



arXiv:1011.4193



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